Relative Gravity Measurement Campaign during the 8th International Comparison of Absolute Gravimeters (2009)

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Z. Jiang[1#], V. Pálinkáš[2#], O. Francis[3], P. Jousset[4], J. Mäkinen[5], S. Merlet[6], M. Becker[7], A. Coulomb[8], K.U. Kessler-Schulz[9], H. R. Schulz[9], Ch. Rothleitner[3], L. Tisserand[1], D. Lequin[4]

1 International Bureau of Weights and Measures (BIPM), Pavillon de Breteuil, F-92312, Sèvres Cedex, France

2 Research Institute of Geodesy, Topography and Cartography, Geodetic Observatory Pecný (GOP), Ondřejov, Czech Republic

3 University of Luxembourg (UL), Luxembourg

4 Bureau de Recherches Géologiques et Minières (BRGM), 3, avenue Claude Guillemin, 45060 Orléans Cedex 2, France

5 Finnish Geodetic Institute (FGI), Masala, Finland

6 Laboratoire National de Métrologie et d'Essais - Systèmes de Référence Temps Espace (LNE-SYRTE), Observatoire de Paris, UMR 8630, UPMC, France

7 Institute of Physical Geodesy, Technische Universität Darmstadt (IPGD), Germany

8 Institut Géographique National (IGN), Saint Mandé cedex, France

9 Angewandte Gravimetrie (AG), Rosengarten, Germany

corresponding authors : zjiang@bipm.org, vojtech.palinkas@pecny.cz

Abstract

The 8th International Comparison of Absolute Gravimeters (ICAG-2009) and the associated Relative Gravity Campaign (RGC2009) took place at the Bureau International des Poids et Mesures (BIPM) between July and October 2009. Altogether 24 institutes with 22 absolute gravimeters and 9 relative gravimeters participated in the ICAG/RGC campaign. Accurate absolute and relative gravity measurements as well as precision levelling measurements were performed on the micro-gravity 3D-grid at the BIPM.

The 2009 comparison was the first to be organized as a Comité International des Poids et Mesures (CIPM) metrological Key Comparison under the CIPM MRA (Mutual Recognition Arrangement), which means that the result will be officially recognized by the governmental organizations responsible. As a consequence, the relative

gravimeters employed were carefully selected and the measurement schedules were rigorously enforced compared to earlier campaigns. Thus the quality of the RGC2009 and the determination of the BIPM local gravity network were improved.

After thirty years and eight successive ICAGs, the BIPM has decided to transfer its role to the National Metrological Institutes, although the CIPM will continue to organize the key comparison as ICAGs. The background to the RGC2009, and the organization, data processing and final results of the gravity and vertical gravity gradients are presented in this paper. This report is more detailed than previous final reports of the RGCs.

Keywords: relative gravimetry, absolute gravimetry, vertical gravity gradient, ICAG, RGC, Key Comparison

Notation

ICAG: International Comparison of Absolute Gravimeters

RGC: Relative Gravity Campaign organized in association with ICAG

AG: absolute gravimeter

RG: relative gravimeter

KC: CIPM key comparison

WB: BIPM watt balance

1 μ**Gal** = 10^{-8} m s^{-2}

g: measured absolute acceleration due to gravity in μGal (minus a constant value of 980 900 000 μGal)

G: adjusted *g* value

KCRV: KC reference value of *G*

δg, δG: differences of *g* or *G*

H: height in meters above the ground benchmark

$\boldsymbol{\gamma}_H$: average gradient corresponding to the height *H*

RMS: root mean square error given by a least-squares adjustment (1-σ statistic estimation)

Mean: mean value of a data set

Std: standard deviation

u: standard uncertainty

Site, Station and **point**: The BIPM gravity network comprises indoor and outdoor relative measurement ties between 5 *sites* (A, B, C1, C2 and WB) and 12 *stations* (Figures 2.2.1, A, B, B1–B6, C1, C2, W1 and W2). The WB site is used for the BIPM watt balance project. Results at the WB site are not discussed in this paper. This paper therefore is limited to 4 sites and 10 stations. At each station, 3 points are defined at 0.30 m, 0.90 m and 1.30 m above the ground benchmark (C1 and C2 have only 2 points at 0.90 m and 1.30 m). There are 28 points in total. Naming convention is by station plus height in cm, e.g. A.030, A.090 and A.130.

1. Introduction

The 8th International Comparison of Absolute Gravimeters (ICAG) and accompanying Relative Gravity Campaign (RGC) took place at the BIPM between July and October 2009 [1,3]. The 2009 comparison was the first organized as a Comité International des Poids et Mesures (CIPM) metrological Key Comparison under the CIPM MRA (Mutual Recognition Arrangement) [2], and the result will be officially recognized by the responsible governmental organizations. The goals of the RGC, as mandated in the Technical Protocol of the ICAG-2009 [1] are: (a) to support the ICAG as a CIPM key comparison (Figure 1.1); (b) to improve and monitor the BIPM local gravity field; (c) to support the BIPM watt balance project. As a consequence of the above, it was decided to carefully select the RGC2009 participating gravimeters and to rigorously follow the measurements schedules, this differs from earlier RGCs when all the data was provided by volunteer participants and all measurements provided to the BIPM were used in data processing. The quality of the determination of the BIPM local gravity network is expected to be significantly improved in RGC2009.

A steering committee (SC) was set up to oversee technical issues of the ICAG and the RGC2009 [1, 3]. The members were: H. Baumann (METAS), M. Becker (IPGD), O. Francis (UL), A. Germak (INRIM), V. Palinkas (RIGTC), H. Wilmes (BKG), L. Vitushkin, L. Robertsson and Z. Jiang (BIPM). The SC was responsible for drafting and approving the Technical Protocol (TP [1]) of ICAG-2009. The TP describes the technical details of the absolute and relative gravity measurements and data processing strategies taking into account the specifications of the CIPM Key Comparison. The SC held two meetings, the first in December 2008 at the BIPM and the second in May 2009 at the Research Institute of Geodesy, Topography and Cartography in the Czech Republic.

Altogether 24 institutes supplied the 22 absolute gravimeters and 9 relative gravimeters that participated in the ICAG/RGC campaigns. The micro-gravity 3D-network at the BIPM was used to perform the absolute and relative gravity measurements as well as precision levelling measurements [17]. Moreover, such a three dimensional gravity mapping is fundamental in the watt balance experiment to transfer an absolute gravity *g* value to the centre of the test mass [18,23]. The goal of the experiment is to link the kilogram to the Planck constant.

In section 2, we present the network structure design and the organization of RGC2009 based on the uncertainty required [1]. In section 3, the results of the relative gravity measurements are discussed together with the uncertainty estimation. The 2009 ICAG/RGC was the last organized by the BIPM and therefore we provide more detailed information and cross-comparisons based on the RGCs that took place in 2001, 2005 and 2009. This paper also serves as a historical document describing the relative gravimetry campaigns undertaken from 2001 onwards. The results in this paper are final and replace preliminary results that have been published in earlier papers and reports.

Figure 1.1 RGC2009 brings the absolute *g*-values measured at different stations (g_0, g_1, g_2, g_3) at different heights to the same reference (g_0 on 0.90 m above the ground benchmark) for comparison.

2. The organization and network of RGC2009

2.1 Participants

In earlier RGCs [4–10,12], participation was open to the wider scientific community. Some participants could not perform the full and rigorous schedule demanded by earlier RGCs due to limits on their time or other conditions. In principle, all the measurements made should be used in the data processing. However, because the quality of the data was not homogeneous, the result of the final adjustment may have been distorted in spite of adequate weighting. Therefore, the Steering Committee decided that in 2009 only well maintained and state-of-the-art gravimeters would be invited. Nine of the best performing relative gravimeters in Europe, from seven organizations with experienced operators participated in the RGC2009. Only gravimeters that allowed automatic digital recording were considered. Table 2.1 lists the participants, the owner organizations and the gravimeters.

Table 2.1 Participants in RGC2009

2.2 The BIPM RGC2009 Network

As illustrated in Figure 2.2.1, the BIPM 3D-grid network comprises 5 sites (A, B, C1, C2 and WB) and 12 stations (A, B, B1, B2, B3, B4, B5, B6, C1, C2, W1 and W2). The sites are stabilized by concrete pillars. The station benchmarks are embedded in the top surfaces of the pillars and the reference points are defined by a cross in the centre of the benchmark on the top surface. The WB site is used for the BIPM watt balance project results of which are not presented in this paper. Interested readers may refer to [18]. The outdoor sites C1 and C2 with 8.8 mGal gravity difference were used for RG scale determination or verification. Our focus is on site B where the absolute measurements related to the ICAG-2009 were carried out.

Figure 2.2.1 The network of RGC2009 with a short baseline between C1 and C2 of 8.8 mGal measured with an absolute gravimeter for the RG scale. There are 28 points in total. Naming convention is by station plus height in cm, e.g. B.030, B.090 and B.130. The stations B, B1, B2 and B5 and B6 were occupied by the AG during the KC of the ICAG-2009

2.3 Consideration of the network structure and the measurement schedule

The major goal of the RGC in the ICAG is to supply the vertical gradients and the gravity differences for the possibility to determine the offsets of the absolute gravimeters within an uncertainty of 1-2 μGal. This is the target value for the total uncertainty of a gravity tie of RGC2009 that has to be ensured. Therefore assuming that the total uncertainty of a relative measurement tie, the so-called one reading tie of one gravimeter, is u_g and the number of the measurements is N, we have $u_g/\sqrt{N} \leq 1$ μGal. Table 2.2 lists the standard uncertainty estimated in a measurement tie of a relative gravimeter. The total combined uncertainty is 3.8 μGal, i.e. if $N \geq 16$, then the required standard uncertainty will be achieved. In the design of the measurement schedule, the number of repeat measurements for a relative horizontal or vertical tie cannot be less than 16. The final reachable standard uncertainty of RGC2009 for a gravity tie is: $\leq 3.8 /\sqrt{16} < 1$ μGal. The standard uncertainty of a vertical gradient is ≤ 2 μGal/m.

Table 2.2 Composition of the standard uncertainty of a gravity tie

Based on the above analysis, the following were considered in the design of the RGC2009 3D-grid network and the measurement schedules:

- To minimize the influence of the uncertainties due to gravimeter zero-drift, measurement set-up, displacement and environmental influences, the measurement schemes had:
  - triangle-closure-based sequence (Figure 2.2.1),
  - short and symmetrical time intervals (Figure 2.3.1.1).
- To avoid errors due to height measurement and vibrations during the measurements, the enforced, fixed-level tripods (Figure 2.4.2) were provided (cf. section 2.4). The tripod enables the gravimeters to occupy 5 different levels at heights of 30, 90, 130, 155 and 170 cm (only 30, 90 and 130 cm were selected at site B) to obtain a robust fit to the vertical gravity gradients using polynomials.
- In addition to the vertical ties, on and between the stations of the sites A, B and WB, horizontal ties were measured at 30, 90 and 130 cm in height. A 3D-grid was established for the first time in 2009.
- Measurement schedules were adapted to each gravimeter for each operator to avoid, as much as possible, any man-made errors [14]. Two schedules, a simple and a full schedule were prescribed. The latter had more closure measurements. E.g. for a vertical gradient measurement, the simple schedule had 7 occupations while a full schedule had 10 occupations. The later had about 30% more measurements than the first. Operators could decide to employ the simple or the full schedule according to his/her situation. But in all cases, the completed schedule had to be fulfilled. Measurements of a half schedule were automatically rejected.

2.3.1 The horizontal δ*g* ties at site B

Horizontal δ*g* measurements at site B were performed at a height of 90 cm for the simple schedule and at heights of 30 cm, 90 cm and 130 cm for the full schedule. The measurements followed two schemes as illustrated in Figure 2.3.1.1: the “odd” scheme for the odd-numbered gravimeters (sequential order 1, 3, 5, 7 and 9 in Table 2.1) and the “even” scheme for the even-numbered gravimeters (2, 4, 6 and 8 in Table 2.1). There were 10 occupations at a height of 90 cm in the simple schedule and 10 occupations at each of 30 cm, 90 cm and 130 cm in the full schedule.

Figure 2.3.1.1 Horizontal δ*g* grid measurement schedules at site B performed separately for heights of 30 cm, 90 cm and 130 cm

Figure 2.3.1.2 The 3D-grid network measurement showing an example of the horizontal ties at the height of 30 cm above the ground bench marks

2.3.2 The vertical δ*g* ties at site B

It is well known that the gravity change above a station can be significantly nonlinear. Since the ICAG 2001, a second degree polynomial is applied as an approximation, cf. [11,12]. The schedule given in Figure 2.3.2 consists of a total of 10 occupations at three levels above ground. The occupations were used to determine the vertical ties at site B. The combination of the horizontal and vertical grids at site B allows creating the 3D-grid network which is necessary for both: (1) the determination of vertical gravity gradients required for the transfer of gravity acceleration determined by AGs at a reference instrumental height to the reference height of the comparison (0.9 m) and (2) the combined adjustment of the ICAG-2009. The mathematical model has been fully discussed in Jiang et al. in 2009 [12].

Figure 2.3.2 Vertical δ*g* measurements at a station with 10 occupations

2.4 Set-up of the gravimeters and tripods

The sensor of a gravimeter is not located in its geometric centre. The plots in Figure 2.4.1 illustrate the sensor location of the Scintrex CG5 and ZLS Burris instruments, according to the manufactures instructions. For the Scintrex CG5, it is 21.1 cm below the top cover of the meter box, 11 cm from the upper edge, and 11.2 cm from the right edge on the top cover as shown in the pictures on the left of Figure 2.4.1. For the ZLS Burris it is 16.9 cm from the top cover of the meter box, 9.6 cm from the bottom edge, and 15.5 cm from the left edge on the top cover as shown in the pictures on the right of Figure 2.4.1.

During RGC2001 and RGC2005, it was found that certain gravimeters suffered vibrations due to the ground noise. The enforced BIPM level-fixed tripods with three movable legs supply a platform to strengthen stability during the measurements (Figures 2.4.2, 2.4.3). Figure 2.4.3 shows a measurement set-up for a ZLS Burris gravimeter for the vertical δg measurements. By choosing different combinations of sub-tripods (Figure 2.4.4 and 2.4.5), the sensors of the gravimeters are placed, within the tolerance of 1 cm, at 30 cm, 90 cm and 130 cm above the ground benchmarks. The height of the top surface of the gravimeter was measured and recorded for each reading. A corresponding gravity correction, using vertical gradient obtained by iteration, was made to account for the difference between the actual height and the required height. The reduction distance is less than 1 cm, and the error in the correction due to the gradient is less than 0.02 μGal and can be ignored. As the uncertainty in the reduction distance is less than 1 mm, this allows a precise measurement of the vertical ties to be made to calculate the vertical gravity gradient at each station.

Figure 2.4.1 The Scintrex CG5 and ZLS Burris relative gravimeters showing the locations of the sensors. The gravimeter's sensor must coincide with the measurement point defined within 1 mm and the orientation is kept the same for each occupation (northwards for ZLS)

Figure 2.4.2 The BIPM enforced tripods with three mobile legs to strengthen stability

Figure 2.4.3 Set-up of a measurement with a ZLS Burris gravimeter on the enforced tripod

Figure 2.4.4 Set-up of the BIPM fixed-level tripod measurements using a Scintrex CG5 at a height of 130 cm at a station

Figure 2.4.5 An assemble of the 4 fixed-height sub-tripods

3. Data processing and the results of RGC2009

The principle of the RGC data processing strategy is given in the technical protocol of ICAG-RGC2009 [1] and is the same as used in the earlier ICAG-RGCs. The following discussion presents only the observation equation used in the adjustment of RGC2009. More details can be found in [12,13]. Data processing was performed using the BIPM software package GraviSoft or Gsoft. This software was especially developed for ICAG data treatment based on the program AdjG, written by the first author for the China gravity basic net 1985 system [16].

3.1 Observation equation

A least squares adjustment of the network was carried out. The unknowns are the linear scale coefficient of the gravimeters and the point gravity values. The starting *g*-value was fixed to the ICAG-2005 result at the point B.090, i.e. 90 cm above the benchmark of station B on site B with G = 28018.8 µGal. The maximum gravity difference between the gravity points within the BIPM yard is about 10 mGal. The linear term of the scale function is adequate for a Scintrex CG5 and ZLS Burris relative gravimeter in the range of 10 mGal. If the linear scale for the gravimeter q is S_q. The zero-drift and the Earth tide free readings at the points i and j are R_i and R_j, of which the corresponding adjusted gravity values are G_i and G_j. The measured relative tie is then $(R_i - R_j)_q$. The observation equation of a tie measured by the relative meter q between points i and j reads:

$$V_{ij} = S_q \times (R_i - R_j)_q - (G_i - G_j). \qquad (3.1\text{-}1)$$

Here V_{ij} is the adjustment residual of the tie $(R_i - R_j)$. The linear scale coefficient S_q is defined with respect to the Scintrex CG5 S348 and S539, which were selected to be of a fixed-scale during the least squares network adjustment, because their scale approximated the best to the baseline C1–C2, and they performed a high quality and full schedule without missing data or outliers. It should be emphasized that only the scales of the S348 and S539 were used. The absolute scale, given by the baseline C1-C2 determined in 2005, was used only to check the scale of these two relative gravimeters. The two scales, relative and absolute, agreed perfectly with each other. From Table 9 of [13], the g-values determined by AG measurements (Ai) are 23281.6 µGal and 32040.4 µGal for C1 and C2, respectively. The difference is −8758.8 µGal. From the Table 3.3.1.3 the difference obtained by RG-only adjustment (scaled by the S348 and S539) is −8758.2 µGal. This difference is 0.6 µGal or relatively 8×10^{-5}, which agrees perfectly with the AG scale. Table 3.1 gives the linear scale coefficients determined with respect to that of the S348 and S539 out of the final RG-only adjustment. It is completely independent of the ICAG-2009 absolute determinations.

Table 3.1 Linear scale coefficients of the relative gravimeters with standard uncertainties

3.2 Vertical gravity gradients

Vertical gravity gradient has to be considered for two reasons. At first the average gradient is needed along the free-fall trajectory of an absolute gravimeter for the straightforward solution of the equation of motion (e.g. for the FG5 gravimeter the dropping distance lies roughly between 1.1 m and 1.3 m above the ground). By equation 3.2-1 and its derivative equation 3.2-2, we can model adequately at the BIPM gravity network [12] the gravity and the vertical gravity gradient at a particular height H as:

$$g(H)=\boldsymbol{a}+\boldsymbol{b}\times H+\boldsymbol{c}\times H^2 \,. \qquad (3.2\text{-}1)$$

$$\boldsymbol{\gamma}_H = \boldsymbol{b} + 2\boldsymbol{c}H, \qquad (3.2\text{-}2)$$

The second application of the gradient is the transfer of the gravity value from the reference height of each gravimeter to the reference height defined for the comparison (0.9 m). For this the transfer correction between the heights H_1 and H_2 is used with equation:

$$\delta g(H_2 - H_1) = g(H_2) - g(H_1) = \boldsymbol{b}(H_2 - H_1) + \boldsymbol{c}(H_2^2 - H_1^2), \qquad (3.2\text{-}3).$$

In addition, the average gradient between the heights H_1 and H_2 can be calculated:

$$\boldsymbol{\gamma}_{(H2+H1)/2} = [g(H_2) - g(H_1)] \,/\, (H_2 - H_1). \qquad (3.2\text{-}4)$$

Therefore, the average gradient between 0.3 m and 0.9 m in height is $\boldsymbol{\gamma}_{0.6m} = (g_{0.9\mathrm{m}} - g_{0.3\mathrm{m}})/0.6\mathrm{m}$ and that between 0.9 m and 1.3 m is $\boldsymbol{\gamma}_{1.1\mathrm{m}} = (g_{1.3\mathrm{m}} - g_{0.9\mathrm{m}})/0.4$ m.

The vertical gradients were determined by using the g-values obtained from the least squares adjustment, at three vertical levels (Figures 2.4.4 and 2.4.5). A second degree polynomial fitting was applied to approximate the gravity value variation along the vertical distance (H) above the ground benchmark. A detailed discussion and conclusion that a second degree polynomial is adequate for the ICAG purpose can be found in Jiang et al. 2009 [12]. As mentioned above, at each station of A and B sites, 3 points were measured at heights of 0.3 m, 0.9 m and 1.3 m. Hence the coefficients a, b and c in the above equation can be uniquely determined and in this case there is no difference between gravity gradients at corresponding height computed using equations 3.2-2 and 3.2-4.

Table 3.2.1 lists the coefficients of the 2nd degree polynomial approach determined during the last three ICAGs in 2001, 2005 and 2009, as well as the gradients at the heights of 0.9 m and 1.2 m ($\gamma_{0.9\mathrm{m}}$ and $\gamma_{1.2\mathrm{m}}$) by equation 3.2-2. Figure 3.2.1 illustrates the gradient variations ($\gamma_{0.6\mathrm{m}}$ and $\gamma_{1.1\mathrm{m}}$) on the pillar B, computed with equation 3.2-4. From the plots of $\gamma_{0.6\mathrm{m}}$ and $\gamma_{1.1\mathrm{m}}$, both have a similar variation tendency, the slope increases from the station B2 at the lowest toward B4 at the highest. The absolute values differ from about 2 to 4 µGal/m, e.g. the contour 295 µGal/m goes through B for $\gamma_{1.1\mathrm{m}}$ while the same contour goes between B and B6 for $\gamma_{0.6m}$.

Table 3.2.1 The parameters of the polynomial for the gradients determined in 2001, 2005 and 2009

Figure 3.2.1 The variations of the gradients over the pillar B, Up: $\gamma_{0.6m}$ and Down: $\gamma_{1.1m}$

Table 3.2.2 The transfer corrections from 0.9 m to different heights of 0.3, 0.8, 1.1, 1.2 and 1.3 m

Table 3.2.3 Differences of the transfer corrections in Table 3.2.2 between 2009–2001 and 2009–2005

A direct comparison between the parameters of the gradients in Table 3.2.1 is not very meaningful. Table 3.2.2 gives the vertical transfer corrections with respect to H = 0.9 m. Table 3.2.3 gives the differences of the transfer corrections listed in Table 3.2.2 between 2009–2001 and 2009–2005. The last line is the RMS of the differences for a particular height. As expected, the highest RMS is obtained for the height of 0.3 m, the longest transfer distance. Indeed, the precision of the transfer correction is near proportional to its length. Compared to the vertical gravity gradients determined in the earlier RGCs, no significant discrepancies were found at site B. The vertical gravity gradient change due to the redistributions of masses is an order of magnitude smaller than the gravity change. The discrepancies and the RMS shown in Table 3.2.3 came from mainly the earlier RGCs. As given in section 2.3, better gravimeters and more rigorous schedules were used in RGC2009. The RMS, hence the uncertainty in the vertical gravity gradient correction, are less than 1 µGal/m for RGC2009. Taking for example the largest RMS at 0.3 m in 2009–2001, of 0.95 µGal/$\sqrt{2}/\delta H$ = 1.12 µGal/m, here δH = 0.6 m. As mentioned above, thanks to the 3D structure of the network RGC2009, the uncertainty in the gradients in 2009 should be much smaller than those in 2001. In fact, the same value was obtained for 2009–2005 of 0.78

µGal/√2/δH = 0.92 µGal/m.

For the time dependent gravity and gradient changes, the historical time series of the vertical gravity gradients at the BIPM reveals interesting features. The first published results date back to 1977, while the first ICAG took place in 1981. Table 3.2.4 shows the vertical gravity gradient measurements between 1977 and 1997. LaCoste-Romberg gravimeters [10] were used to perform measurements between the ground floor and a height of 1 m. The observations were made only at two levels and non-linearities were disregarded. There are obviously two groups: 1977–1984 (276 µGal/m on average) and 1985–1997 (295 µGal/m on average). The difference between 1984-1985 is 19 µGal/m at the same station. Although, we cannot completely exclude the possibility of the measurement error but such a sudden change in the vertical gradient in 1884-1985 may suggest certain mass changes in the close vicinity of the station. A photo taken at that time suggests that the change in 1985 was probably caused by construction works and internal mass redistributions in the office around station A3.

Table 3.2.4 Vertical gravity gradients at the station A3 between 1977 and 1997

3.3 Gravity results of the RGC2009 and the uncertainty analysis

A series of least squares adjustments were carried out by changing the weightings, the outlier detection criteria, the number of meters or other parameters. In this section, we give the final result of RGC2009 (G09) and the uncertainty estimation by different methods: comparisons of the G09 to earlier RGCs in 2001 and 2005 and to the absolute gravity determinations obtained from the ICAG key comparison (KC) in 2009 as well as the analysis of the raw measurement data and the residuals of the adjustment.

3.3.1 *Gravity results of the RGC2009 and comparison with previous results of 2001 and 2005*

Table 3.3.1.1 lists the final gravity results of the RGCs 2001, 2005 and 2009 and the inter-comparisons of the gravity values. During the preparation of this paper, the KC result was approved by the participants of ICAG-2009 but has not yet been published [22]. We use only the differences of the KCRVs which are converted to the B point with the fixed value 28018.8 µGal. The KCRVs defined at the height of 90 cm were computed as an AG-only solution. We can see the G09 agrees perfectly with the KC09' [22]. The differences of 2009–2001 and 2009–2005 at station A and B1 are rather large and have the same sign. A difference of 4 µGal at station A is observed. This could be explained by a height change of about 1 cm between site A and B which was built in 2001 several months before the IGAC2001. However, the result of the repeated precise levelling [17] shows a maximum variation of approximately 2–3 mm between the two sites A and B in the period 2001–2009. There are several other explanations for the detected 4 μGal discrepancy. We cannot exclude the local hydrological effects which can be different at both sites even their distance is only about 200 meters. The pillar has a height of about 2.4 m above the floor level in the basement. Disturbing vibrations were reported during the measurements. The repeatability over site A is always poorer than that of site B. Because the linear scale of the RGs were arbitrarily determined by fixing the scale of one or two RGs (e.g. the gravimeters S008 and S245 were selected as the scale reference for RGC2005), the influence of the linear scale cannot be completely excluded. The most probable seems to be the explanation by errors in measurements, e.g. another outlier is of B1 at a height of 30 cm. The difference between 2001 and 2009 is −4.1 μGal and it cannot be explained by the above described sources. As mentioned above, more than half of the gravimeters supplied in 2001 were voluntary. These gravimeters did not perform complete schedules and therefore the results are less reliable than those of 2009.

Table 3.3.1.1 Final gravity results of RGC 2001 (G01), 2005 (G05) and 2009 (G09)

(δG is the gravity difference between the heights of 0.9–0.3 m and 1.3–0.9m; the $G01'$ is the RGC2001 value converted to B.090 point (G = 28018.8 μGal), KC09′ is the KCRV converted to the B.090 point)

Figure 3.3.1.1 illustrates the gravity variations on pillar B at the heights of 0.3 m, 0.9 m and 1.3 m. As shown, the gravity values close to the ground (0.3 m) vary more rapidly than those at higher surfaces of 0.9 m and 1.3 m.

Figure 3.3.1.1 Gravity variations on pillar B at the heights of 0.3 m, 0.9 m and 1.3m

Table 3.3.1.2 Gravity differences (δG2009) between the points at the height of 0.3 m (upper triangle) and 1.3 m (lower triangle)

Unlike the previous RGCs in 2001 and 2005, when only the horizontal ties between the points at a height of 0.9 m were measured, in RGC2009 the horizontal ties at heights of 0.3 m and 1.3 m of the 3D network were also measured. Table 3.3.1.2 lists the adjusted gravity differences δG2009. The values in the upper triangle above the diagonal are those of 0.3 m in height and those in the lower triangle are of 1.3 m. The values in the upper triangle in Table 3.3.1.3 are those of 0.9 m and the values in the lower triangle are the differences of δG2009–δG2005. As observed above, the discrepancies of the outdoor ties are rather large due to possible measurement errors and the linear scale of the RGs. Excluding sites A, C1 and C2, the mean value of the discrepancies of δG2009–δG2005 is 0.5 μGal with a standard deviation of ±1.1 μGal. Compared with other ties, the ties linked to B6 have rather large discrepancies between 2009 and 2005 results. The mean and the standard deviation without B6 are 0.06±0.89 μGal.

Table 3.3.1.3 Gravity differences (δG2009) between points at the height of 0.9 m (upper triangle) and the difference between that of δG2005

3.3.2 Measurement errors from a relative gravimeter shown in earlier studies and adjusted residual analysis

The RG meters used in RGC2009 were ZLS Burris and Scintrex CG3 and CG5. For the first time the ZLS Burris performed a full schedule and no LaCoste-Romberg (LCR) meters took part. The Burris Gravity Meter™ is manufactured by the ZLS Corporation, Austin, Texas, USA. Its design is based on the invention by L. LaCoste and A. Romberg, of the zero length spring (ZLS). The Burris gravimeter works with a metal spring. A digital feedback system is used to null the beam, taking full advantage of the latest development in digital technology. The data recording resolution is 1 μGal and data reading repeatability is 1–3 μGal within 50 mGal [19]. The Scintrex Autograv CG3 and CG5 gravity meters are manufactured by Scintrex Limited, Ontario, Canada. They are the quartz spring gravimeters. The straightforward sensor design without micrometer screws or gearboxes and astatization does not require any periodical calibration terms or high order polynomial calibration function. Therefore, a complex calibration procedure is no longer necessary. For gravity ties with short distance of local and micro-gravimetric nets, the measurement accuracy is ±1 μGal [20]. In earlier experiences [10, 11 and 12], we have not observed considerable difference in the measurement uncertainties between the CG3 and CG5. RGC2009 proved also the conclusions drawn in the above studies [19, 20 and 21].

Figure 3.3.2 Histograms of the adjusted residuals of the best two gravimeters ZLS Burris B020 and Scintrex CG5 S539

The whole network was adjusted together with all the data from the 9 relative gravimeters. The residuals and their distribution provide the noise level of the measurement of a relative gravimeter. Figure 3.3.2 displays the histograms of the residuals of the gravimeters ZLS Burris B020 and Scintrex CG5 S539. The total number of measured ties of ZLS Burris B20 is 119 of which the RMS is 1.0 µGal. That of the Scintrex CG5 S539 is 143 and 1.3 µGal, respectively. These are the two best cases. Table 3.3.2 provides statistics of the residuals of all 9 gravimeters. The RMS varies from 1.0 to 2.7 µGal and on average 1.9 µGal with a total of 1418 measured ties. In Table 2.2 above in section 2.2, the total estimated uncertainty in a single RG tie is 3.8 µGal which is much larger than the RMS 1.9 µGal on obtained average. This implies that the final uncertainty is better than or equal to 1 µGal. The residual analysis and the independent studies prove that the original objective of the aimed uncertainty has been achieved. The two models of gravimeters ZLS Burris and Scintrex CG5 both had a good performance and their results agreed well with each other.

Table 3.3.2 Residual statistics of the 9 gravimeters in the RGC2009

3.3.3 Raw measurement errors of a relative gravimeter by triangle closures

Table 3.3.3 Statistics of the triangle closures of the raw measurement data

The measurement scheme was designed on the basis of the triangle-close measurement schedule, see sections 2.2 and 2.3.1. A non-zero-triangle-closure is considered a true error. The analysis of the amplitude of the closures of the raw measurement data (corrections for tides, drift and sensor heights are included) provides a range of the measurement uncertainty. A detailed discussion on the pre-processing of the raw data was given in [12]. Table 3.3.3 presents the closures of the 11 triangles. The triangle closures were calculated by first taking the average of all the raw measurements of a tie and then taking the sum of the three ties which compose an independent triangle. The mean value equals 0.03 and the RMS equals 0.38 µGal. Similarly as in section 3.3.2, this again proves that the desired uncertainty of 1 µGal of a tie has been achieved.

3.3.4 Comparison of the gravity differences obtained by RGC2009 and by the ICAG-2009 KC

During the KC ICAG-2009, 9 absolute gravimeters (AG) occupied the 5 stations on the site B: B, B1, B2, B5 and B6. The adjusted gravity differences (δG_{KC}) at the height of 0.9 m are listed in the upper triangle in Table 3.3.4. In the upper triangle of Table 3.3.1.3 the gravity differences of RGC2009 (δG2009) are given. The differences in the $\delta G_{\mathrm{KC}}-\delta G$2009 are given in the lower triangle of Table 3.3.4. The mean value and the standard deviation are -0.32 ± 0.13 μGal and are significantly below the measurement uncertainty. Nevertheless, systematic character of differences is also evident but it reaches an insignificant absolute value. This suggests that the RG and AG measurements fully agree with each other at the level of a few tenths of a microgal. In fact, in the ICAG-2009 KC report the mean and the standard deviation of the differences in the AG offsets determined by the AG-only and RG-only solutions are -1.0 ± 0.4 μGal. Here, the mean value -1 μGal comes mainly from the starting values, that of the RG-only is the *g*-value of B.090 of ICAG-2005 while that of AG-only is of the KCRV 2009 *g*-value.

Table 3.3.4 KC gravity differences (δG_{KC}) between stations at the height of 0.9 m (upper triangle) and the difference from that of δG2009

4. Conclusions

RGC2009 was organized to support (a) the ICAG-2009 which was the first CIPM metrological key comparison, (b) to further investigate the BIPM local gravity field and (c) to backup the BIPM watt balance project. A 3D-grid network was set up using relative and absolute gravimeters. High precision relative gravity and levelling observations were performed according to well designed measurement schedules. RGC2009 was the most laborious and rigorous RGC in ICAG history. The required standard uncertainty of 1 μGal in the final adjusted gravity tie was fulfilled. This was proven by analysing the raw and adjusted data as well as comparing the AG-only data of ICAG-2009. The agreement between the RG-only results and the AG-only results is better than 1 μGal for all gravity differences between individual stations. In this paper, we also compared the results of the relative gravimetry carried out for the purposes of ICAG-2001, 2005 and 2009. Because, at least for the near future, ICAG/RGC2009 was the last campaign organized and held by the BIPM, we present the technical details in this paper. The paper serves also as a technical and historical document of the ICAGs/RGCs conducted to date.

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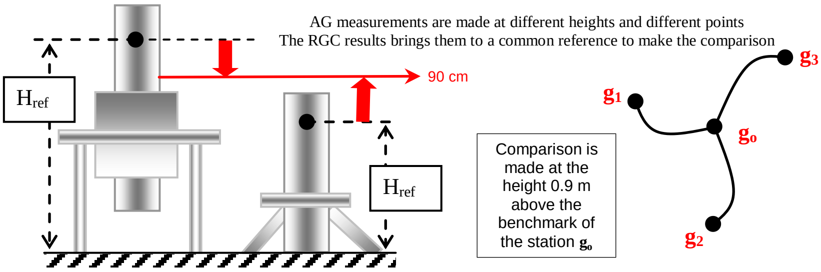


Figure 1.1 RGC2009 brings the absolute *g*-values measured at different stations (g_0, g_1, g_2, g_3) at different heights to the same reference (g_0 on 0.90 m above the ground benchmark) for comparison.

Table 2.1 Participants in RGC2009

Participating organizations and Operators	Relative Gravimeters
Angewandte Gravimetrie, Germany: H. R. Schulz, K. U. Kessler-Schulz	ZLS Burris B025
RIGTC, Geodetic Observatory Pecny (GOP), Czech Rep.: V. Palinkas	ZLS Burris B020
BIPM: L. Tisserand, Z. Jiang	Scintrex CG5 S348
University of Luxembourg: O. Francis, Ch. Rothleitner	Scintrex CG5 S008/S010
FGI, Finland: J. Mäkinen	Scintrex CG5 S052
LNE-SYRTE, France: S. Merlet	Scintrex CG5 S105
BRGM, France: P. Jousset, D. Lequin	Scintrex CG5 S028/S539

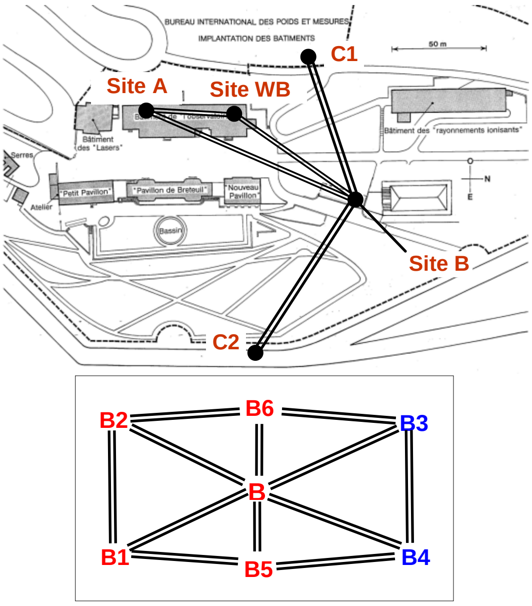
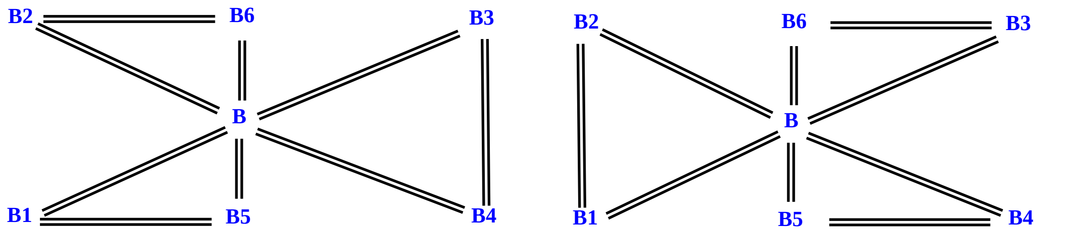


Figure 2.2.1 The network of RGC2009 with a short baseline between C1 and C2 of 8.8 mGal measured with an absolute gravimeter for the RG scale. There are 28 points in total. Naming convention is by station plus height in cm, e.g. B.030, B.090 and B.130. The stations B, B1, B2 and B5 and B6 were occupied by the AG during the KC of the ICAG-2009

Table 2.2 Composition of the standard uncertainty of a gravity tie

Source of uncertainty	***u*** /µGal
Resolution of gravimeter readout	1.0
Scale factor	0.5
Feedback and non-linearity	0.5
off-level effect	1.0
Environmental effects (e.g. Temperature)	1.5
Transport/Displacement	1.0
Atmosphere pressure correction	0.1
Eccentricity of gravimeter sensor	1.5
Tidal corrections	0.5
Zero-drift correction	1.5
Others	2.0
Total (u_g)	**3.8**



Odd schema: B-B1-B5-B-B2-B6-B-B3-B4-B for the gravimeters S348, S008, S105, S539 and B25

Even schema: B-B1-B2-B-B3-B6-B-B4-B5-B for the gravimeters S010, S028, S052 and B020

Figure 2.3.1.1 Horizontal δg grid measurement schedules at site B performed separately for heights of 30 cm, 90 cm and 130 cm

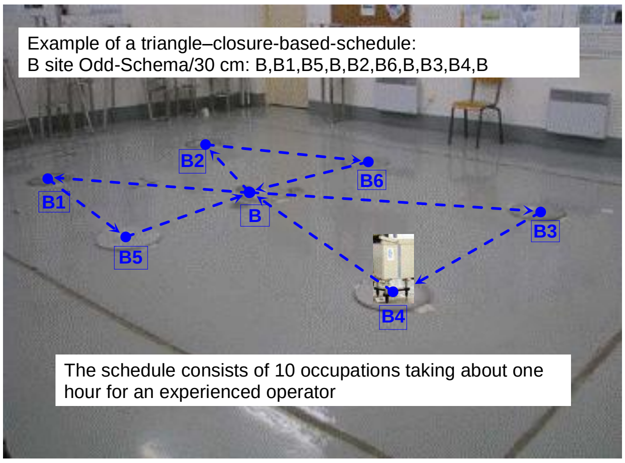


Figure 2.3.1.2 The 3D-grid network measurement showing an example of the horizontal ties at the height of 30 cm above the ground bench marks

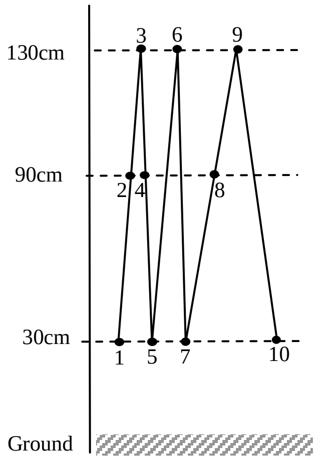


Figure 2.3.2 Vertical δg measurements at a station with 10 occupations

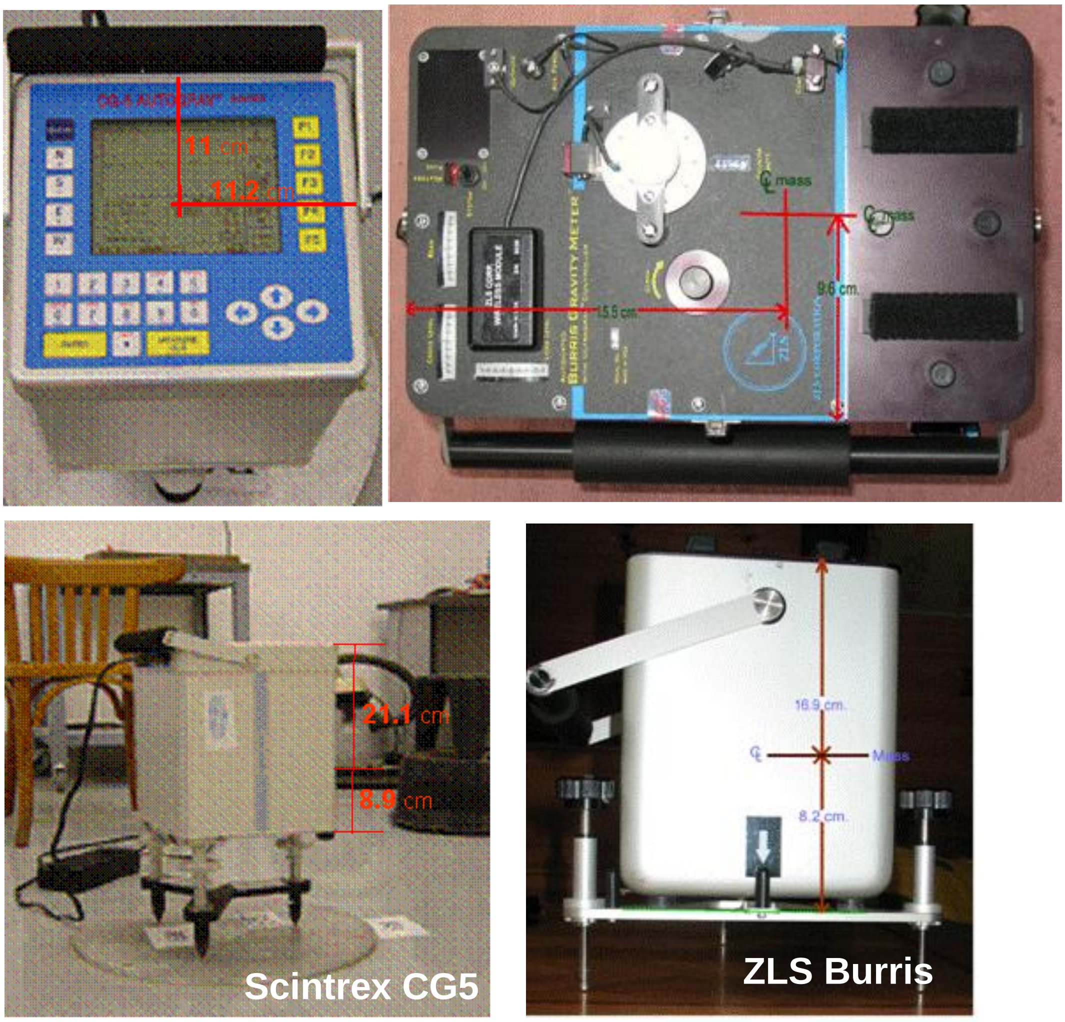


Figure 2.4.1 The Scintrex CG5 and ZLS Burris relative gravimeters showing the locations of the sensors. The gravimeter's sensor must coincide with the measurement point defined within 1 mm and the orientation is kept the same for each occupation (northwards for ZLS)

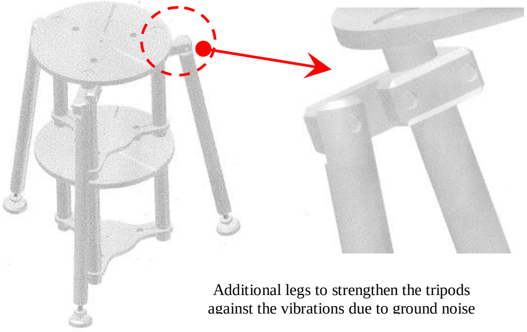


Figure 2.4.2 The BIPM enforced tripods with three mobile legs to strengthen stability

Figure 2.4.3 Set-up of a measurement with a ZLS Burris gravimeter on the enforced tripod

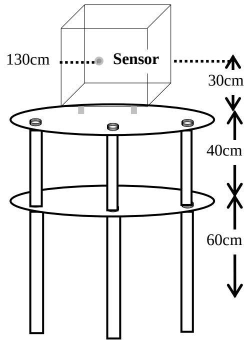


Figure 2.4.4 Set-up of the BIPM fixed-level tripod measurements using a Scintrex CG5 at a height of 130 cm at a station

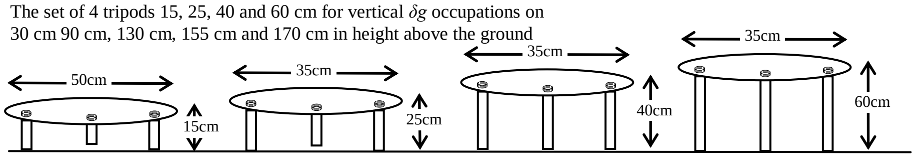


Figure 2.4.5 An assemble of the 4 fixed-height sub-tripods

Table 3.1 Linear scale coefficients of the relative gravimeters with standard uncertainties

Metre	Scale	RMS
S348	1.0000000	
S539	1.0000000	
S008	0.9984789	±0.0002661
S010	0.9939564	±0.0002400
B020	0.9983870	±0.0002360
B025	0.9973556	±0.0002259
S028	0.9943434	±0.0010573
S052	1.0017001	±0.0011152
S105	0.9989688	±0.0003113

Table 3.2.1 The parameters of the polynomial for the gradients determined in 2001, 2005 and 2009

	2001				2005				2009			
	b µGal/m	***c*** µGal/m²	$\gamma_{0.9m}$ µGal/m	$\gamma_{1.2m}$ µGal/m	***b*** µGal/m	***c*** µGal/m²	$\gamma_{0.9m}$ µGal/m	$\gamma_{1.2m}$ µGal/m	***b*** µGal/m	***c*** µGal/m²	$\gamma_{0.9m}$ µGal/m	$\gamma_{1.2m}$ µGal/m
A	-322.69	9.8	-305.1	-299.2	-315.73	6.583	-303.9	-299.9	-312.37	3.917	-305.3	-303.0
A2	-324.14	12.7	-301.3	-293.7	-320.17	9.167	-303.7	-298.2				
B	-300.81	2.1	-297.0	-295.8	-300.47	1.917	-297.0	-295.9	-301.37	2.667	-296.6	-295.0
B1	-302.39	8.1	-287.8	-283.0	-296.93	5.083	-287.8	-284.7	-295.57	4.917	-286.7	-283.8
B2					-289.30	4.000	-282.1	-279.7	-290.77	4.667	-282.4	-279.6
B3	-310.70	9.0	-294.5	-289.1	-311.43	8.833	-295.5	-290.2	-304.77	4.667	-296.4	-293.6
B4					-307.50	3.750	-300.8	-298.5	-312.23	6.583	-300.4	-296.4
B5					-297.03	0.583	-296.0	-295.6	-302.57	3.667	-296.0	-293.8
B6					-300.03	5.583	-290.0	-286.6	-296.73	4.083	-289.4	-286.9

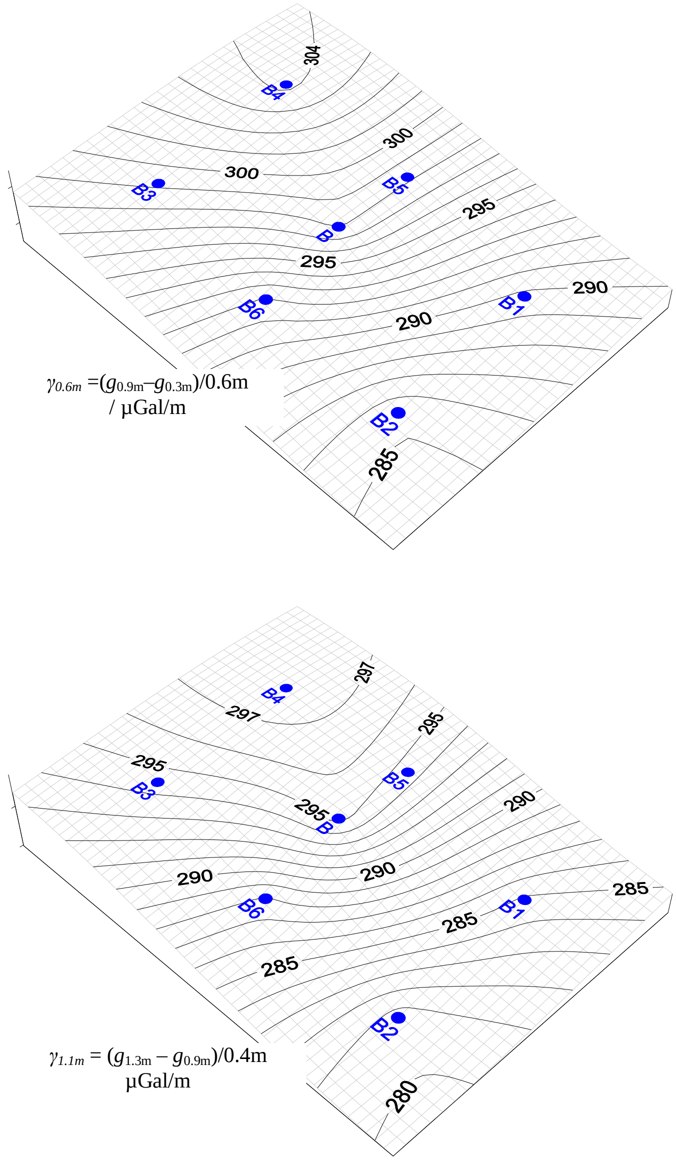


Figure 3.2.1 The variations of the average gradients over the pillar B, Up: $\gamma_{0.6m}$ and Down: $\gamma_{1.1m}$

Table 3.2.2 The transfer corrections from 0.9 m to different heights of 0.3, 0.8, 1.1, 1.2 and 1.3 m

	2001 / µGal					**2005** / µGal					**2009** / µGal				
H	0.3m	0.8m	1.1m	1.2m	1.3m	0.3m	0.8m	1.1m	1.2m	1.3m	0.3m	0.8m	1.1m	1.2m	1.3m
A	186.6	30.6	-60.6	-90.6	-121.4	184.7	30.5	-60.5	-90.6	-121.2	184.6	30.6	-60.9	-91.2	-121.9
A2	185.3	30.3	-59.7	-89.2	-119.8	185.5	30.5	-60.4	-90.3	-120.9					
B	179.0	29.7	-59.3	-88.9	-118.7	178.9	29.7	-59.3	-88.9	-118.7	178.9	29.7	-59.2	-88.7	-118.5
B1	175.6	28.9	-57.2	-85.6	-114.6	174.5	28.8	-57.4	-85.9	-114.8	173.8	28.7	-57.1	-85.6	-114.4
B2						170.7	28.3	-56.3	-84.3	-112.6	171.1	28.3	-56.3	-84.3	-112.7
B3	179.9	29.5	-58.5	-87.5	-117.3	180.5	29.6	-58.8	-87.9	-117.7	179.5	29.7	-59.1	-88.5	-118.3
B4						181.8	30.1	-60.0	-89.9	-120.1	182.6	30.1	-59.8	-89.5	-119.8
B5						177.8	29.6	-59.2	-88.7	-118.4	178.9	29.6	-59.0	-88.5	-118.2
B6						176.0	29.1	-57.8	-86.5	-115.7	175.1	29.0	-57.7	-86.4	-115.5

Table 3.2.3 Differences of the transfer corrections in Table 3.2.2 between 2009–2001 and 2009–2005

	2009–2001 / µGal					**2009–2005 /** µGal				
H	0.3m	0.8m	1.1m	1.2m	1.3m	0.3m	0.8m	1.1m	1.2m	1.3m
A	-1.96	-0.03	-0.29	-0.61	-0.46	-0.10	0.12	-0.39	-0.67	-0.74
B	-0.07	-0.04	0.11	0.19	0.22	0.00	-0.04	0.12	0.20	0.23
B1	-1.80	-0.14	0.09	0.04	0.25	-0.70	-0.11	0.21	0.30	0.41
B2						0.40	0.03	-0.03	-0.02	-0.07
B3	-0.44	0.14	-0.55	-0.95	-1.01	-1.00	0.04	-0.33	-0.63	-0.59
B4						0.80	-0.01	0.19	0.37	0.32
B5						1.10	0.03	0.13	0.28	0.19
B6						-0.90	-0.07	0.06	0.04	0.15
RMS	0.95	0.12	0.32	0.54	0.60	0.78	0.07	0.23	0.41	0.43

Table 3.2.4 Vertical gravity gradients at the station A3 between 1977 and 1997

(* an outlier in ICAG 81 was not given in the table)

Year	**γ µGal/m**	**RMS**	**Source**
1977	273	3	Cannizzo et. al. 1977
1980	273	7	Sakuma
1981	284	1.6	ICAG 1981*
1984	275	1.9	Ogier, 1986
1985	295	1.2	ICAG 1985
1985	296	4.6	Ogier, 1986
1986	295	1.2	Röder &Wenzel, 1986
1989	297	0.7	ICAG 1989
1994	293	1.5	ICAG 1994
1997	293.3	1.5	ICAG 1997
1985-1997	294.9	1.8	Mean

Table 3.3.1.1 Final gravity results of RGC 2001 (G01), 2005 (G05) and 2009 (G09)

(δG is the gravity difference between the heights of 0.9–0.3 m and 1.3–0.9m; the $G01'$ is the RGC2001 value converted to B.090 point (G = 28018.8 µGal), KC09′ is the KCRV converted to the B.090 point)

Pt	***H***	***G*09** /µGal	**MRSE** /µGal	***δG*** /µGal	***G*05** /µGal	***G*01** /µGal	***G*01'** /µGal	***G*09 –*G*05** /µGal	***G*09 –*G*01'** /µGal	***G*09 –KC09'** /µGal
A	0.3	25889.3	1.1	-184.6	25886.6	25887.6	25887.1	2.7	2.2	
A	0.9	25704.7	1.1	-121.5	25701.9	25701.2	25700.7	2.8	4.0	
A	1.3	25583.2	1.2		25581.4	25580.4	25579.9	1.8	3.3	
B	0.3	28197.7	1.1	-178.9	28197.7	28197.6	28197.1	0.0	0.6	
B	0.9	**28018.8**	**1.1**	**-118.2**	**28018.8**	**28019.3**	**28018.8**	0.0	0.0	0.0
B	1.3	27900.6	1.1		27900.3	27900.2	27899.7	0.3	0.9	
B1	0.3	28186.4	1.1	-173.8	28187.8	28191.0	28190.5	-1.4	-4.1	
B1	0.9	28012.6	1.1	-113.9	28013.3	28015.6	28015.1	-0.7	-2.5	0.3
B1	1.3	27898.7	1.1		27899.0	27901.4	27900.9	-0.3	-2.2	
B2	0.3	28168.9	1.1	-171.1	28168.3			0.6		
B2	0.9	27997.8	1.1	-112.2	27997.6			0.2		-0.4
B2	1.3	27885.6	1.1		27885.4			0.2		
B3	0.3	28182.3	1.1	-179.5	28182.2	28183.3	28182.8	0.1	-0.5	
B3	0.9	28002.8	1.1	-117.8	28001.7	28002.3	28001.8	1.1	1.0	
B3	1.3	27885.0	1.1		27884.9	27886.4	27885.9	0.1	-0.9	
B4	0.3	28198.2	1.1	-182.6	28197.6			0.6		
B4	0.9	28015.6	1.1	-119.1	28015.8			-0.2		
B4	1.3	27896.5	1.1		27896.1			0.4		
B5	0.3	28199.1	1.1	-178.9	28198.3			0.8		
B5	0.9	28020.2	1.1	-117.8	28020.5			-0.3		-0.1
B5	1.3	27902.4	1.1		27902.2			0.2		
B6	0.3	28174.5	1.1	-175.1	28173.8			0.7		
B6	0.9	27999.4	1.1	-115.1	27997.8			1.6		-0.6
B6	1.3	27884.3	1.1		27882.7			1.6		
C1	0.9	23280.5	1.2		23281.6			-1.1		
C2	0.9	32038.7	1.2		32040.3			-1.6		
							Mean	0.39	0.15	-0.16
							Std	1.08	2.39	0.35

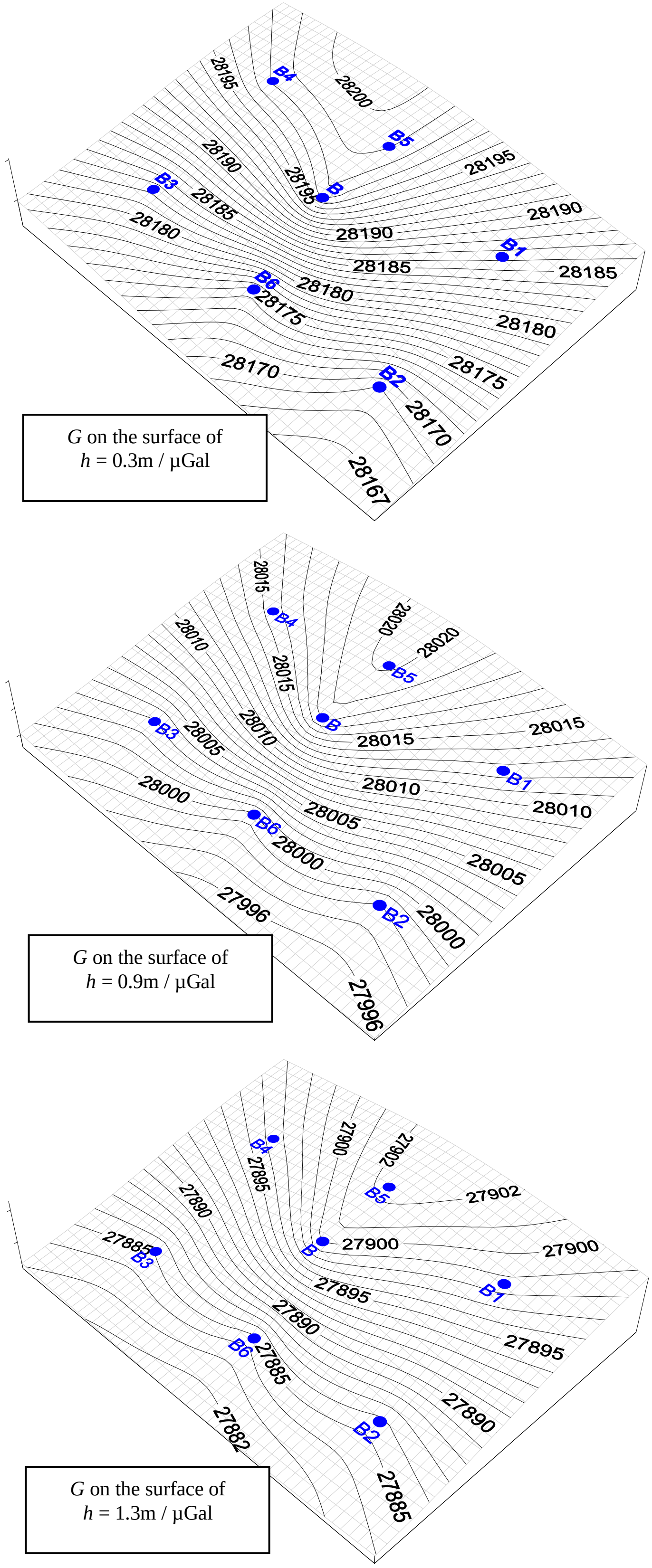


Figure 3.3.1.1 Gravity variations on pillar B at the heights of 0.3 m, 0.9 m and 1.3m

Table 3.3.1.2 Gravity differences (δG2009) between the points at the height of 0.3 m (upper triangle) and 1.3 m (lower triangle)

Pt		A	B	B1	B2	B3	B4	B5	B6
	δG	δG / µGal on H = 0.3m							
A	δG / µGal on H = 1.3m		-2308.4	-2297.1	-2279.6	-2293	-2308.9	-2309.8	-2285.2
B		2317.4		11.3	28.8	15.4	-0.5	-1.4	23.2
B1		2315.5	-1.9		17.5	4.1	-11.8	-12.7	11.9
B2		2302.4	-15	-13.1		-13.4	-29.3	-30.2	-5.6
B3		2301.8	-15.6	-13.7	-0.6		-15.9	-16.8	7.8
B4		2313.3	-4.1	-2.2	10.9	11.5		-0.9	23.7
B5		2319.2	1.8	3.7	16.8	17.4	5.9		24.6
B6		2301.1	-16.3	-14.4	-1.3	-0.7	-12.2	-18.1	

Table 3.3.1.3 Gravity differences (δG2009) between points at the height of 0.9 m (upper triangle) and the difference between that of δG2005

Pt		**A**	**B**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**
	δG	δG2009 / µGal on H = 0.9m									
A	δG2009- δG2005/ µGal on H = 0.9m		-2314.1	-2307.9	-2293.1	-2298.1	-2310.9	-2315.5	-2294.7	2424.2	-6334.0
B		-2.8		6.2	21.0	16.0	3.2	-1.4	19.4	4738.3	-4019.9
B1		-3.5	-0.7		14.8	9.8	-3.0	-7.6	13.2	4732.1	-4026.1
B2		-2.6	0.2	0.9		-5.0	-17.8	-22.4	-1.6	4717.3	-4040.9
B3		-1.7	1.1	1.8	0.9		-12.8	-17.4	3.4	4722.3	-4035.9
B4		-3.0	-0.2	0.5	-0.4	-1.3		-4.6	16.2	4735.1	-4023.1
B5		-3.1	-0.3	0.4	-0.5	-1.4	-0.1		20.8	4739.7	-4018.5
B6		-1.2	1.6	2.3	1.4	0.5	1.8	1.9		4718.9	-4039.3
C1		-3.9	-1.1	-0.4	-1.3	-2.2	-0.9	-0.8	-2.7		-8758.2
C2		-4.4	-1.6	-0.9	-1.8	-2.7	-1.4	-1.3	-3.2	-0.5	

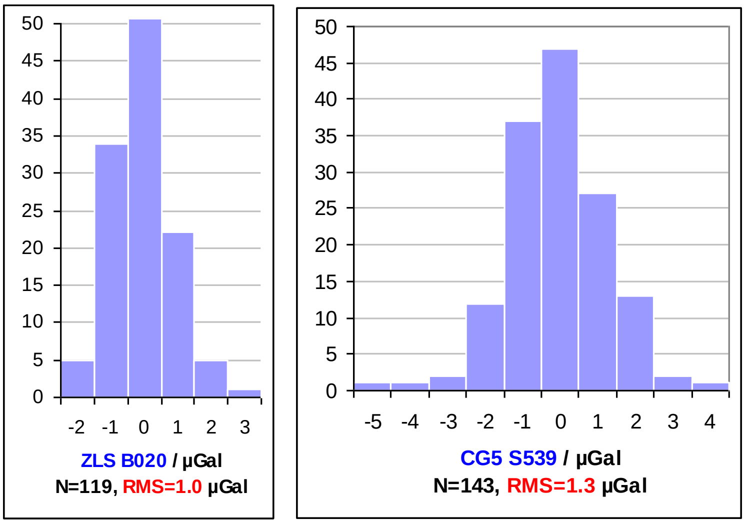


Figure 3.3.2 Histograms of the adjusted residuals of the best two gravimeters ZLS Burris B020 and Scintrex CG5 S539

Table 3.3.2 Residual statistics of the 9 gravimeters in the RGC2009

Gravimeter	**Number of ties**	**RMS of resid. /μGal**
S008	115	2.3
S010	121	2.0
B020	119	1.0
B025	236	1.6
S028	69	2.1
S052	92	2.7
S105	211	1.7
S348	312	1.6
S539	143	1.3
ALL	1418	1.9

Table 3.3.3 Statistics of the triangle closures of the raw measurement data

No	Triangle			Closure/µGal
1	B	B1	B2	0.2
2	B	B2	B6	0.6
3	B	B6	B3	-0.2
4	B	B3	B4	-0.2
5	B	B4	B5	-0.1
6	B	B5	B1	-0.3
7	W1	A	B	-0.4
8	W2	15	16	0.2
9	W2	21	22	-0.1
10	W2	19	20	-0.1
11	W2	17	18	0.7

Table 3.3.4 KC gravity differences (δG_{KC}) between stations at the height of 0.9 m (upper triangle) and the difference from that of $\delta G2009$

Pt		B	B1	B2	B5	B6
	δG	δG_{KC} on H = 0.9m / μGal				
B	$\delta G2009–\delta G_{KC}$/μGal		6.5	20.6	-1.5	18.8
B1		0.3		14.1	-8.0	12.3
B2		-0.4	-0.7		-22.1	-1.8
B5		-0.1	-0.4	0.3		20.3
B6		-0.6	-0.9	-0.2	-0.5	